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Effects of climate change on discharge behaviour of the river Rhine

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ABSTRACT

Recently, the Royal Netherlands Meteorological Institute (KNMI) presented four new climate scenarios for the Netherlands. These new scenarios will serve as the national standard in water management adaptation policies in the Netherlands for the coming years. The main part of the Rhine basin lies upstream of Lobith and outside of the Netherlands and thus the discharge regime of the Rhine is determined by its upstream hydrological behaviour. In the current paper the effects of climate change on the discharge of the river Rhine at Lobith are assessed, projecting the new KNMI climate change scenarios on the entire river basin. To do this, the semi-distributed conceptual hydrological HBV model for the Rhine basin was used. Transforming 35 years of historical climate forcing data generated the meteorological input series, which resulted in projected changes in mean discharges of the Rhine. In addition, with the aim to analyse effects on extreme events with return periods smaller than 1/200 years, output of a stochastic weather generator was used to create meteorological input series of 1,000 years for different climate scenarios, resulting in several sets of 1,000 years of daily discharge data.

INTRODUCTION

It is expected that climate change will have major implications for the discharge regime of the Rhine basin. Seasonal discharge will shift to more discharge in winter and less discharge in summer, and the frequencies of floods and droughts are expected to increase (Kwadijk, 1993; Middelkoop et al., 2001; Te Linde, 2006). Recent climate change research focuses on simulating changes in the magnitude and frequencies of flood events using different predictive models.

On 30 May 2006, the Royal Netherlands Meteorological Institute (KNMI) presented four new climate scenarios for the Netherlands (Van den Hurk et al., 2006) which are referred to as KNMI'06 scenarios. It is in the interest of Dutch water managers to have an idea of the impact of climate change on the discharge regime of the river Rhine and the question has risen whether recent adjustments in modeling methods and when using the new climate scenarios, will change existing expectations.

Recently, Van Deursen (2006) assessed the effects of climate change on the discharge of the river Rhine using the distributed grid-based model RhineFlow by projecting the KNMI'06 scenarios on the entire basin of the Rhine. The semi-distributed lumped HBV model has been used in multiple studies on discharge generation in the Rhine basin (Eberlet et al, 2005; Weerts & Van der Klis, 2004). It is for example used to run long time series, which can then be used to assess return periods of extreme events for the Rhine branches in the Netherlands. For this last application the precipitation is provided by a stochastic weather generator (Beersma et al, 2001).

In the current paper the HBV model for the Rhine is used to assess the effect of climate change on the discharge, using the KNMI'06 scenarios. Transforming 35 years of historical climate forcing data generated meteorological input series. This resulted in projected changes in mean discharges of the Rhine. In addition, with to aim to analyse effects on extreme events with return periods smaller than 1/200 years, output of a stochastic weather generator was used to create meteorological input series of 1,000 years for different climate scenarios

METHODS

The Rhine basin

The entire Rhine basin covers an area of 160,800 km^2 upstream of Lobith, which is located at the Dutch-German border and where the river Rhine has an average discharge of 2,200 m^3/s. The discharge is influenced by the amount and timing of precipitation, snow storage and snow melt in the Alps, the evaporation surplus during the summer period, and changes in groundwater and soil water storage (Pinter et al., 2006).

HBV

The HBV model (Hydrologiska Byråns Vattenbalansavdelning) (Bergström, 1976; Lindström et al., 1997) is a semi-distributed conceptual model that simulates discharge on a daily basis for 134 sub-basins of the Rhine. The model consists of different routines in which snowmelt is computed by a day-degree relation, and groundwater recharge and actual evaporation are functions of actual water storage in a soil box. Discharge formation is represented by three linear reservoir equations and the sub-basins are linked together with a simplified Muskingum approach to simulate routing processes. The HBV model was developed for the Rhine in 1999.

Rainfall generator and FEWS Extreme Discharges simulations

A historical data set for the period of 1961-1995 of daily temperature and precipitation data is available at 36 stations in the Rhine basin. Using nearest-neighbor resampling and these 35 years of historical data, the rainfall generator creates series of 1,000 years of synthetic precipitation and temperature values, which can then be used as input data for hydrological modeling of the Rhine basin. For a detailed description of the method, see Beersma et al. (2001).

FEWS Extreme Discharges (Werner & Reggiani, 2002) is instrumentation in support of determining the frequency of occurrence of extreme discharge events in the Rhine basin. Using the 1,000 years synthetic precipitation and temperature series as generated by the rainfall generator, 1,000 years of runoff is calculated using the HBV model. Rather than taking the traditional approach of fitting and extrapolating extreme value distributions, the approach taken here attempts to calculate these extreme value distributions using continuous model simulation, where the period of simulation is in the same order as the return period of the event of interest. The Gumbel distribution appears to fit best at extreme discharge values of the Rhine basin and is used as generalized extreme value distribution.

Climate scenarios

On 30 May 2006, the KNMI (Royal Dutch Meteorological Institute) presented four new climate scenarios for the Netherlands, which are referred to as KNMI'06 scenarios (Van den Hurk et al., 2006). These KNMI'06 scenarios will serve as the national standard in adaptation policies in the Netherlands for the coming years. General Circulation Model (GCM) simulations show changes in the strength of the seasonal mean western component of the large-scale atmospheric flow in the area around the Netherlands. That is why besides temperature, this circulation is used as steering parameter. Also potential evaporation is affected greatly by the assumed circulation change. The values chosen for global temperature increase and atmospheric circulation change are used as steering parameters to discriminate the four scenarios for the Netherlands, and are summarized in Table 1. In the current paper, only results are displayed and discussed of the G and W+ scenarios, which represent the mildest and the most extreme scenario, and by that means the spread of all four scenarios. No discrimination in probability exists between the four climate scenarios.

Table 1. Values for the steering parameters used to identify the four KNMI'06 climate scenarios for 2050 relative to 1990.

Scenario		Global Temp. Increase	Change of atmospheric circulation	
G	Moderate	+1 ºC	Weak	
G+	Moderate +	+1 ºC	Strong	- Milder and wetter winters due to more westerly winds - Warmer and drier summers due to more easterly winds
W	Warm	+2 ºC	Weak	
W+	Warm +	+2 ºC	Strong	- Milder and wetter winters due to more westerly winds - Warmer and drier summers due to more easterly winds

Delta approach

The different climate scenarios for the Rhine basin were constructed by applying simple transformation rules to observed temperature and precipitation, also referred to as the delta change approach (Lenderink et al., 2007). This simple delta approach for temperature just adds an expected temperature increase to the observed temperature record to obtain a future temperature series. Precipitation was perturbed by a fraction. These rules leave the present day variance of temperature and the coefficient of variation of precipitation unchanged. Also, changes in the number of precipitation days and potential changes in the correlation between different variables are not considered. Furthermore, the transformation was applied for the whole Rhine basin, not taking into account possible geographical differences.

The scenario time series are given by:

$$T_{scen,d*}(t) = T_{his,d}(t) + \left(\overline{T}_{scen,d} - \overline{T}_{his,d}\right)$$

$$P_{scen,d*}(t) = P_{his,d}(t) \times \left(\frac{\overline{P}_{scen,d}}{\overline{P}_{his,d}}\right)$$

where T_{scen} is the scenario temperature in ºC, T_{his} the historical temperature in ºC, P_{scen} the scenario precipitation in mm, P_{his} the historical precipitation in mm, $d*$ the day in future time series and d the day in reference time series.

Evaporation in HBV is implemented by a file describing mean monthly values of potential evaporation for all HBV sub catchments. To transform the evaporation data this file was perturbed by a fraction.

RESULTS

Results are available for several locations (Te Linde, 2006) of which only results at Lobith are displayed and discussed in the current paper. Mean monthly discharges and changes in extreme value distributions are presented for the G and W+ scenarios. In the current paper, the generated historical discharges by HBV for the period 1961-1995 are not compared to the measured historical discharge for the period 1961-1995. Personal notes that do describe such a comparison (Buiteveld, 2005), show that HBV represents mean discharge values very well, but tends to overestimate discharge above 10,000 m^3/s at Lobith by +/- 10%.

Change in mean discharges

Figure 1 displays the predicted mean change at Lobith, both in absolute and relative values. The mean rise in discharge in the winter months December, January and February varies from ~ 200 m^3/s (8%) rise for the G scenario to ~ 400 m^3/s (16%) for the W+ scenario. In the summer months June, July and August, the discharge changes only minor in the G scenario. The W+ scenario (remember the strong changes of atmospheric circulation) though, shows a decrease in mean discharge of ~ 750 m^3/s (42 %).

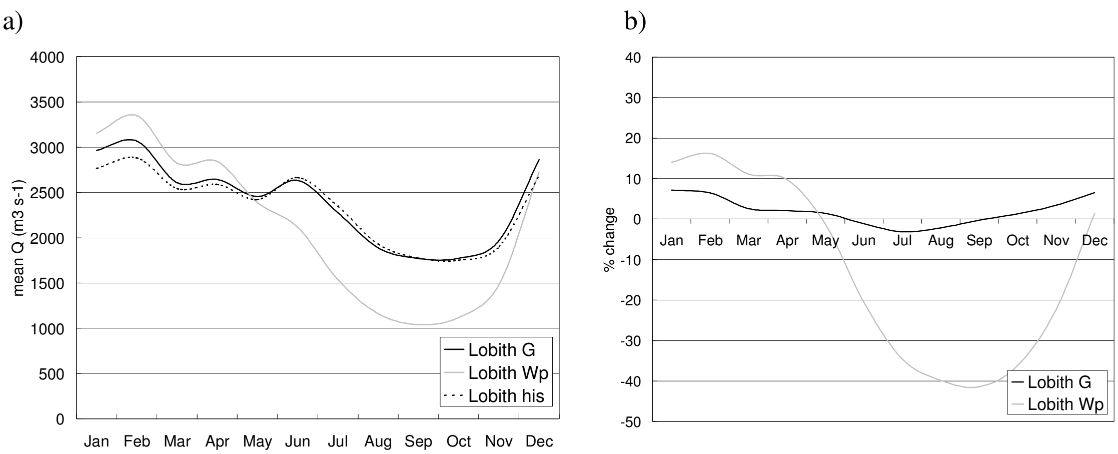

Figure 1. Mean change in discharge at Lobith, a) absolute values and b) relative values

Change in extreme value distributions

Figure 2 displays Gumbel plots of the yearly maxima of the simulated daily discharge at Lobith for 1,000 years of discharge based on 1961-1995 meteorological input data and the G and W+ climate scenarios input data. The W+ scenario shows the most extreme increase in extreme values when compared to the G scenario. Apparently all very extreme discharge events occur in the winter months, when the W+ scenario displays more increase in precipitation and temperature rise, than the G scenario does.

Also in Figure 2, a straight line displays the fitted Gumbel distributions. The Gumbel distribution is hereby fitted without threshold values. The fit therefore does not take into account the observed downwards bend of the most extreme values. The downward bend seems to include approximately the same extreme events for all scenarios, and does not occur at a fixed discharge value.

Table 2 shows a summary of the Gumbel extreme value distribution fit for the dataset representing the recent situation and the two climate scenarios. When looking at a return period of 1,250 years, the dataset based on the period 1961-1995 results in an estimated discharge of 18,349 m^3/s, which is more than 2,000 m^3/s higher than the currently adopted value of 16,000 m^3/s at Lobith that is based on 100 years of measured discharge values. This is due to the earlier mentioned way of fitting the Gumbel distribution without a threshold, which causes the fit to lie above the highest calculated discharges. The G scenario returns a discharge of 19,424 m^3/s at a return period of 1,250 years, which is 5.8%

higher than the dataset based on the historical period 1961-1995. The W+ scenario returns a discharge of 22,076 m^3/s at a return period of 1,250 years, which is 20% higher than the dataset based on the period 1961-1995 and 13% higher than the G scenario.

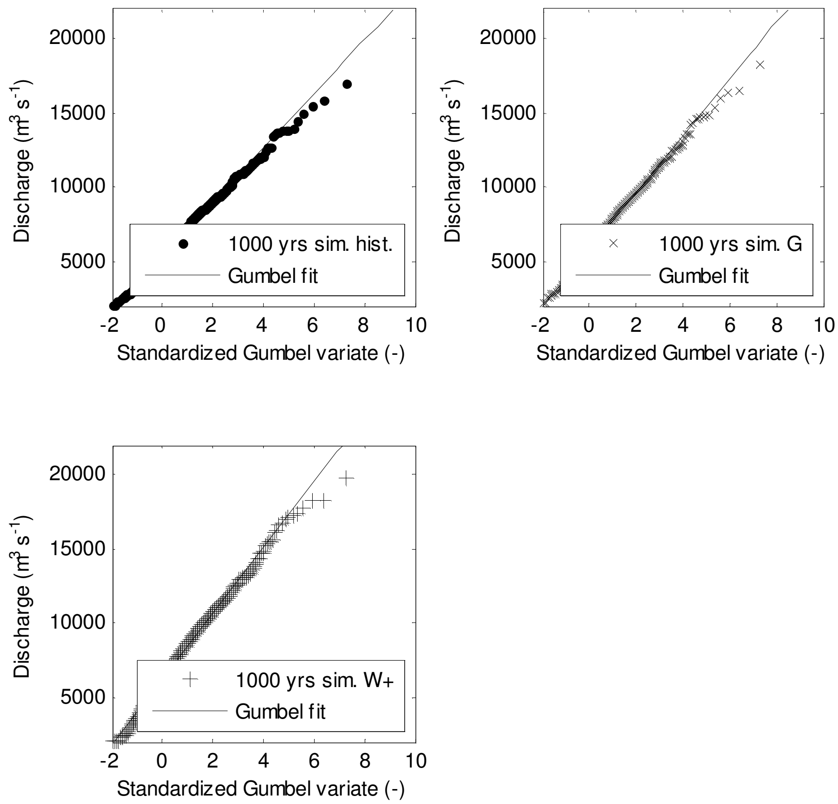

Figure 2. Gumbel distribution and Gumbel fit of yearly maximum of 1,000 years of simulated discharge at Lobith, based on historical meteorological data for 1961-1995 and climate scenario G and W+.

Table 2. Extreme values analysis and Gumbel fit at Lobith

Return period (years)	Gumbel fit of yearly maximum of 1,000 years of simulated discharge, based on:		
	Historical meteorological data	Climate scenario G	Climate scenario W+
100	13,776	14,588	16,447
500	16,692	17,672	20,036
1,000	17,946	18,997	21,580
1,250	18,349	19,424	22,076

DISCUSSION AND CONCLUSIONS

All climate runs using the KNMI'06 scenarios for the year 2050 as input data, show an increase in mean winter discharges and a decrease in mean summer discharges for the Rhine basin. There is a wide range in these predicted changes, especially in the summer decrease, depending on the input scenario. At Lobith, the maximum increase in mean winter discharge is 16%, and the maximum summer decrease is 42%, both the result of the most extreme climate change scenario W+. The moderate climate scenario G shows 8% increase in winter discharge and minor changes in summer values at Lobith. The extreme value analysis of the 1,000-year runs by FEWS Extreme Discharges, resulted in the W+ scenario showing the most extreme increase in extreme values (20%) when compared to the G scenario (5.8%).

It can be concluded that the expected changes in temperature and precipitation due to climate change, very likely will result in changes in the discharge regime in the Rhine basin. By looking at relative changes in discharge instead of absolute changes for both scenarios, many errors and model uncertainties can be neglected. Even though the trend of expected changes is displayed here, these results must be considered and treated as preliminary results. It should be noted that the transformation of climate forcing data according to climate scenarios is done in a simplified matter. At this moment, it is not clear how well these scenario datasets of precipitation and temperature for the Rhine basin, represent the future climate scenarios, as presented by the KNMI for the Netherlands. Research is ongoing, which will produce more statistically adapted and geographically varied, meteorological input datasets for the Rhine basin.

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